Seasonal Variations in the Physical Environment of the Ponds at the Hawaii Marine Laboratory and the Adjacent Waters of Kaneohe Bay, Oahu[1]

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INTRODUCTION

KANEOHE BAY, located on the northeastern, or windward, side of the island of Oahu, Territory of Hawaii, is approximately 7.3 nautical miles long and 2.5 nautical miles wide, with 3.8 nautical miles fronting on the Pacific. It covers an area of 14.1 square nautical miles. The entrance is protected for almost all its length by coral reefs and has only two deep channels into the adjacent ocean. Within the bay are numerous coral reefs with channels 30 to 60 feet deep between them. Adjacent to the shores the bay has broad shoal areas of mud or sand that usually terminate in steep fronts of growing coral. Numerous small streams flow into the bay, but none of these carries much water except at times of the extremely heavy rainfall during southerly, or "kona," storms.

Located approximately 1.5 nautical miles from the southeastern shore of the bay and 0.3 nautical miles from the closest land to the southwest is a small island, Moku o Loe or "Coconut Island." The island is about 18 acres in area and reaches a height of 55 feet. Originally it was surrounded by broad coral flats of sand and mud, with growing coral on the margins. However, a previous owner of the island had numerous channels dredged to the edge of the island, the dredged coralline material being thrown up to form jetties protecting the channels. In one area a series of fish ponds was constructed. The ponds are separated by the coral fill and are connected by concrete spillways into which screens can be fitted. The sides of these ponds which are almost vertical were constructed either of disc-shaped coral heads or of concrete. The bottom of the ponds is covered with a fine silt, similar to that covering most of the bottom of Kaneohe Bay.

With the establishment of the Hawaii Marine Laboratory on the island and the projected use of these ponds for holding experimental fish, it became desirable to learn of the changes in the physical environment in the ponds as contrasted to those in the adjacent waters. This study attempts to fill this need and, in addition, provides information of more general interest as no study of seasonal variation in inshore marine environments has been made in Hawaii heretofore or, as far as can be ascertained, in other regions of the tropical Central Pacific. Moreover, no study of seasonal variation of enclosed waters in Hawaii has been made heretofore, although ponds somewhat similar to the ones studied have long been used in Hawaii for rearing fish commercially.

The study, as carried out, fell into four sections: first, the survey of the ponds to determine their dimensions and depths; second, the study of currents and tides in the pond area, the study of the tides being necessary for later sections of the study; third, the study of the meteorology—rainfall, wind, and air temperature—and water temperature, and its correlation with the changes in the ponds and adjacent waters; and fourth, an investigation principally of changes in the chlorinity and the oxygen content of the water.

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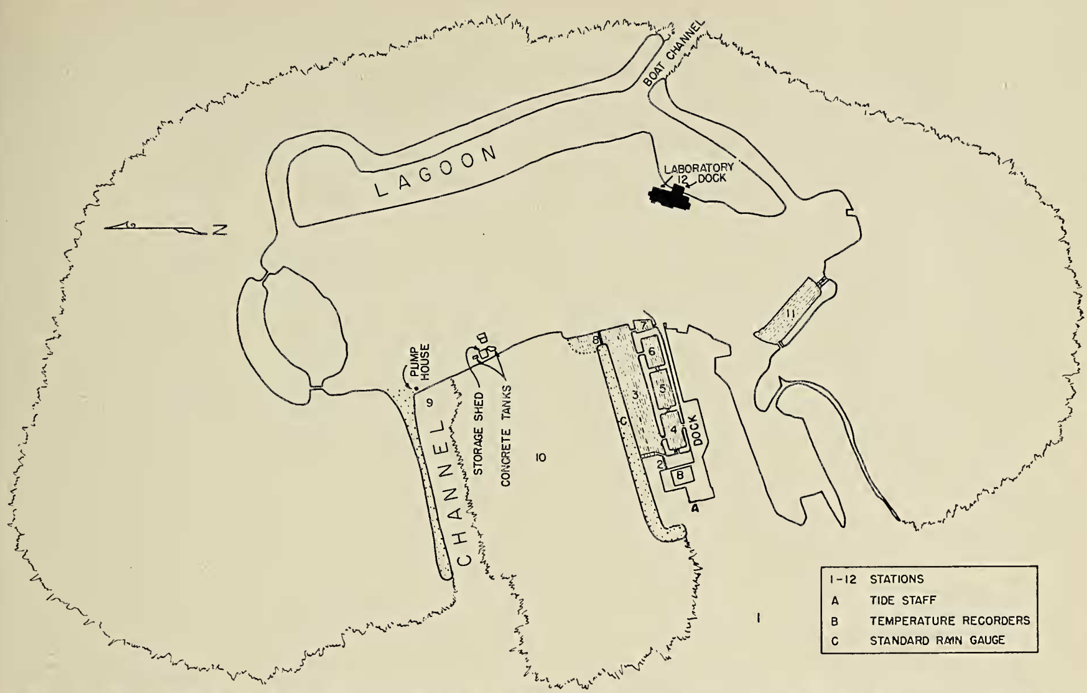

FIG. 1. Map of Moku o Loe, "Coconut Island," and vicinity showing stations, tide staff, temperature recorders, and standard rain gauge.

In the course of the 24 months' investigation, 12 stations were established, 11 for the first portion of the study, with the last station in front of the Hawaii Marine Laboratory added for the last 19 months. For convenience of reference the stations have been numbered as indicated in Figure 1. Stations 3 to 7 and 11 were located in the ponds; station 2 was in the open water immediately adjacent to the ponds; station 10 on the coral flat, exposed at extreme low water and near the principle series of ponds; and station 1 in the channel off the island where the water is about 60 feet deep. This last station was used as typical of the open water of the bay. These stations were visited weekly for the first 14 months of the study and monthly for the next 10 months. The period during which the study was carried on covered the period from February 19, 1949, to January 17, 1951.

Three 24-hour cycles of observations were made to record diurnal changes in tide, temperature, chlorinity, and oxygen content. The dates of these three periods were selected to permit comparison of the different seasons.

MENSURATION OF PONDS

The ponds and some adjacent waters were surveyed to permit the drawing of charts with depth contours and the estimation of volumes and volume exchanges in the ponds. The surveys were made in the following manner: At regular intervals along the length of a pond or channel, the distances depending on the length and the configuration of the body, a length of line marked off every 6 feet was stretched across the pond. Then the observer, either by wading or swimming, took a sounding with a lead line at the marked intervals. The depths were recorded to the nearest quarter foot. Tidal readings were taken before and after surveying each pond so depths could be reduced to the zero tide line (the marine datum line, 0.8 feet below mean sea level in Honolulu). The tidal readings throughout the entire period varied only about 2 inches because at the time selected for the survey there was a "vanishing tide" with its long station-

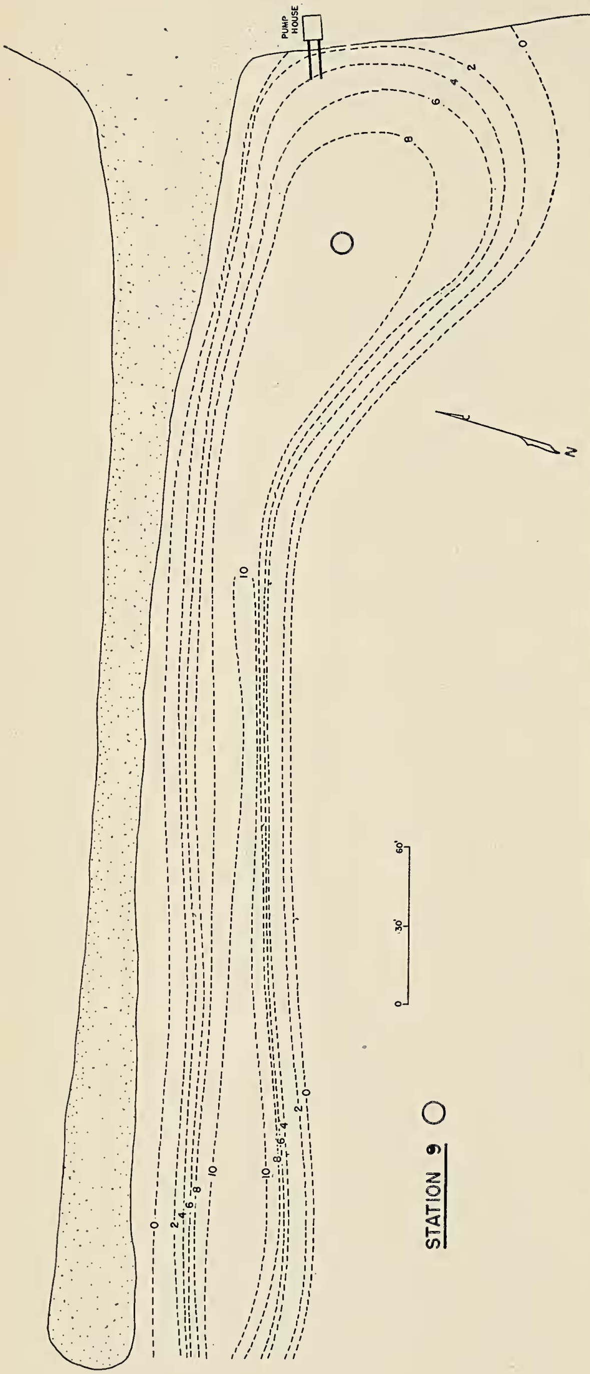

FIG. 2. Contour map of channel between coral spit and tidal flat showing depth in feet and location of station 9.

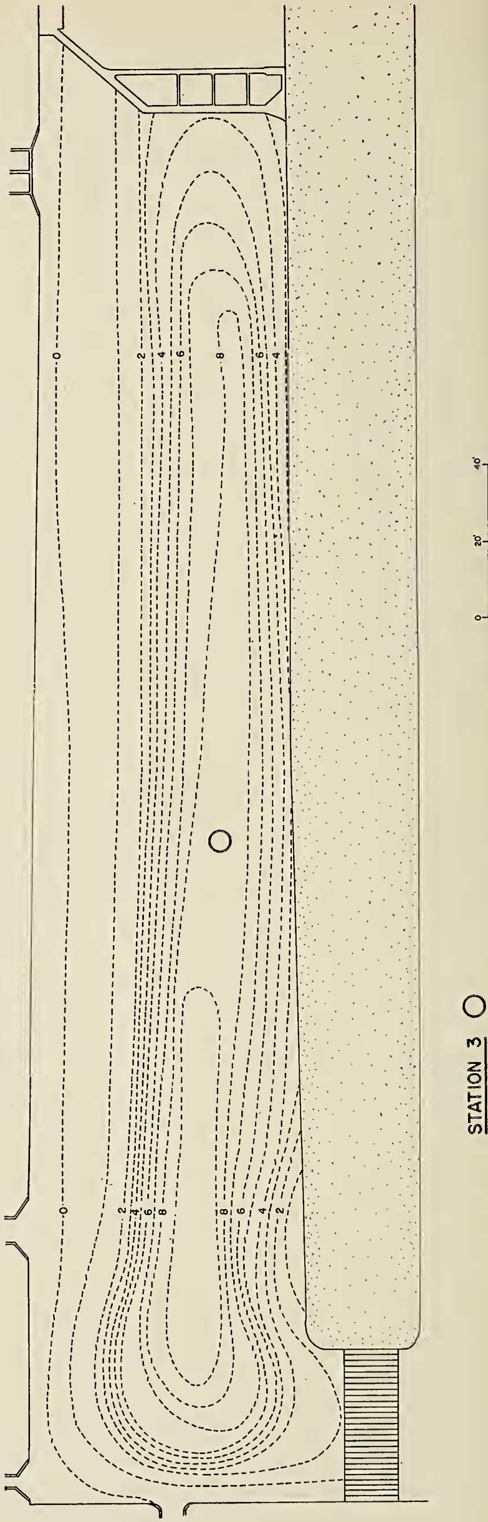

FIG. 3. Contour map of pond 5 showing depth in feet and location of station 3.

ary phase. These corrected values formed the basis of the depth contours of the maps (Figs. 2 to 8). Contours were drawn not only from the location of the soundings but also from the known configuration of the ponds and channels.

Areas of the different contours in the ponds were then obtained by means of a polar planimeter (for description and use see Welch, 1948: 79–82). Using these data, the volumes of the several ponds were then determined, using the method outlined by Welch (1948: 95). The volumes of the several ponds are shown in Table 1.

The volumes of average and maximum tidal exchange as well as the percentage exchanges in volume at mean and maximum tidal range were computed on the basis of these area and volume figures. The volumes of average tidal exchange are the product of the area at the zero tide line and the mean range of tide. The percentage exchanges in volume at mean tide range were obtained by dividing the volume of average tidal exchange by the total pond volume at mean high water. The volumes of maximum tidal exchange are the sum of the maximum volume above and the minimum volume below the zero tide line; that is, the result of multiplying the pond area (at zero tide) by the difference in height between the lowest and highest tide. The percentage exchanges in volume at maximum tidal range were obtained by dividing the volume of maximum tidal exchange by the total pond volume at the maximum high water. The values for minimum and maximum height of tides and the mean range of tide were calculated from the 1949 Tide Tables for Waikane, Kaneohe. The value for mean low water was obtained from the United States Coast and Geodetic Survey. Inasmuch as the walls above the zero tide line are almost vertical, the volumes for the higher tides were based on the area at the zero tide line. The values for pond 11 were not computed because the shoreward margin of the pond is gradually sloping and irregular.

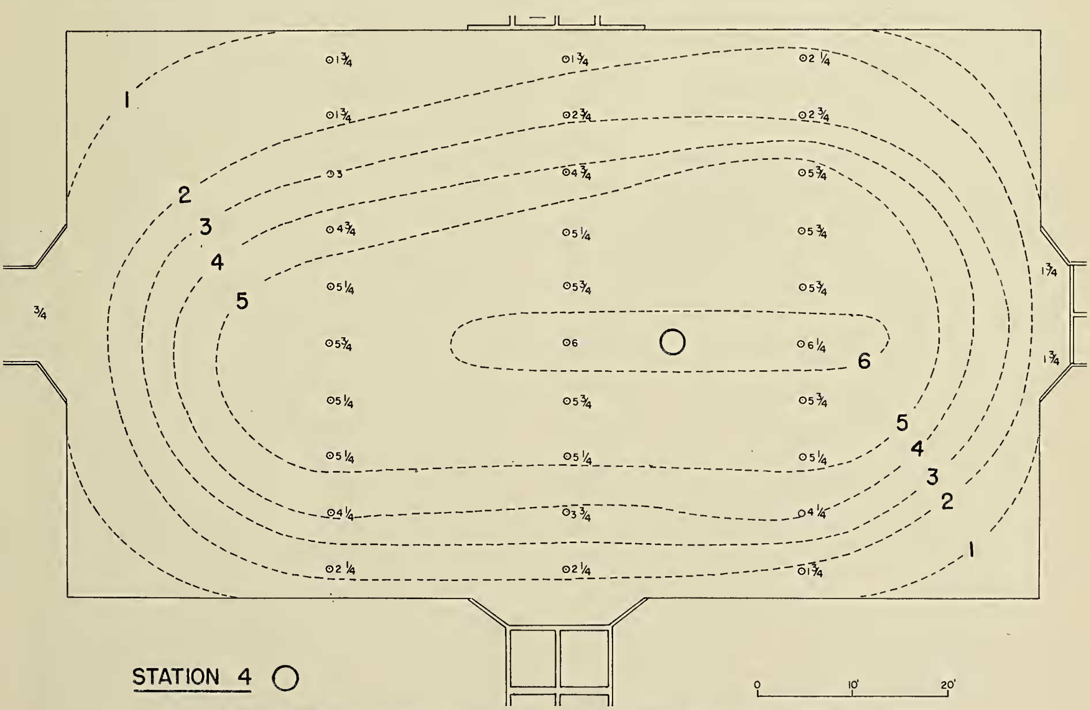

FIG. 4. Contour map of pond 1 showing depth in feet and location of station 4.

TABLE 1
AREA, VOLUME, AND VOLUME EXCHANGE OF THE PONDS AND BOAT CHANNEL

POND	AREA	VOLUME AT ZERO TIDE	VOLUME OF AVERAGE TIDAL EXCHANGE	PERCENTAGE EXCHANGE IN VOLUME AT MEAN TIDAL RANGE	VOLUME OF MAXIMUM TIDAL EXCHANGE	PERCENTAGE EXCHANGE IN VOLUME AT MAXIMUM TIDAL RANGE
	Square feet	*Cubic feet*	*Cubic feet*			
1	5,800	21,000	8,100	26	19,300	51
2	5,400	8,000	7,500	43	18,100	75
3	4,000	5,100	5,600	46	13,600	80
4	1,700	2,300	2,400	45	5,680	78
5	23,000	97,000	32,000	23	75,100	46
Channel	33,000	200,000	47,000	18	110,000	37

CURRENTS AND TIDES

Tidal current patterns were noted in ponds 1 to 5 of the main pond systems. Observations were made on two flood and two ebb tides, with winds of force 3–4 coming from the north on the flood tides, and winds of force 0–2 coming from the southwest and west on the ebb tides. To trace the water flow a saturated solution of fluorescein dye in sea water was poured into the water at various points. The movements of the fluorescein dye were noted at intervals, the total time of observation for each pond depending on the speed of the dye movements.

The currents on the flood tides reach the ponds by way of the channels north and west of the net house (Fig. 1, B), and on the ebb tides they leave the ponds by the same route; that is, currents enter and leave ponds 1 and 5 from the adjacent channels, enter and leave pond 2 mostly through pond 1, and enter and leave the smaller ponds, 3 and 4, through pond 5, though some slight water exchange exists between ponds 2 and 3. On the flood tides no currents were observed entering pond 5 by way of the tide flats (Fig. 1, 10). Instead, water coming in from the channels moved onto the flats.

Short-period reversals of flow several minutes in length were noted, especially on the flood tides and at some of the gates. It was not in the scope of this study to investigate the phenomenon, but it is suggested that perhaps these reversals may be either the result of long-period waves sweeping over the outer reef and reaching the island as imperceptible changes in water level or the cumulative result of interference patterns of the smaller off-shore waves.

As it was not possible to establish an automatic tide gauge on the island, approximations of the tide were made using a tide staff. The height of the tides was recorded in inches above an arbitrary zero level by means of a tide staff nailed to the dock (Fig. 1, A). A series of comparisons, including those of the three diurnal cycles, was made between the observed Kaneohe tide and the theoretical Honolulu tide. The times of high and low water as well as the amplitude of the tidal curves were compared.

The regularity of tidal movements is subject to the influences of wind. For example, it is generally known that an onshore wind tends to raise the level and an offshore wind tends to lower the level of the sea along a coast. Steady winds did not affect the times of high and low water but merely their heights. Variable winds, on the other hand, not only affect the heights but also the times of high and low water. In an enclosed bay such as Kaneohe, with its wide shallow front as entrance and two comparatively narrow channels as exits, a period of high onshore winds can raise the sea level higher and maintain

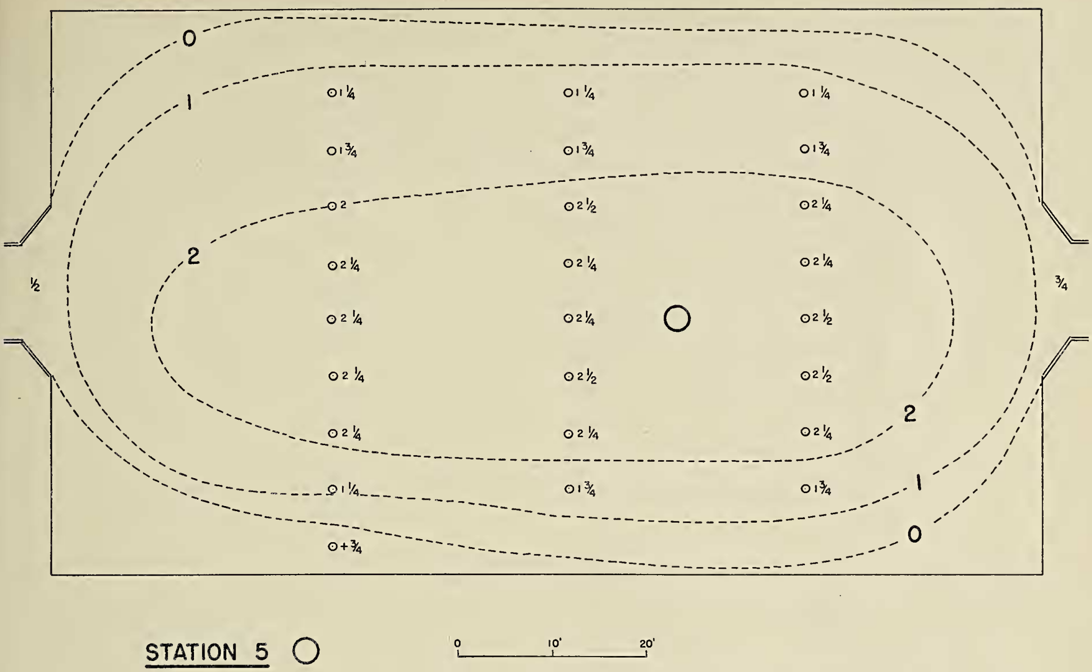

FIG. 5. Contour map of pond 2 showing depth in feet and location of station 5.

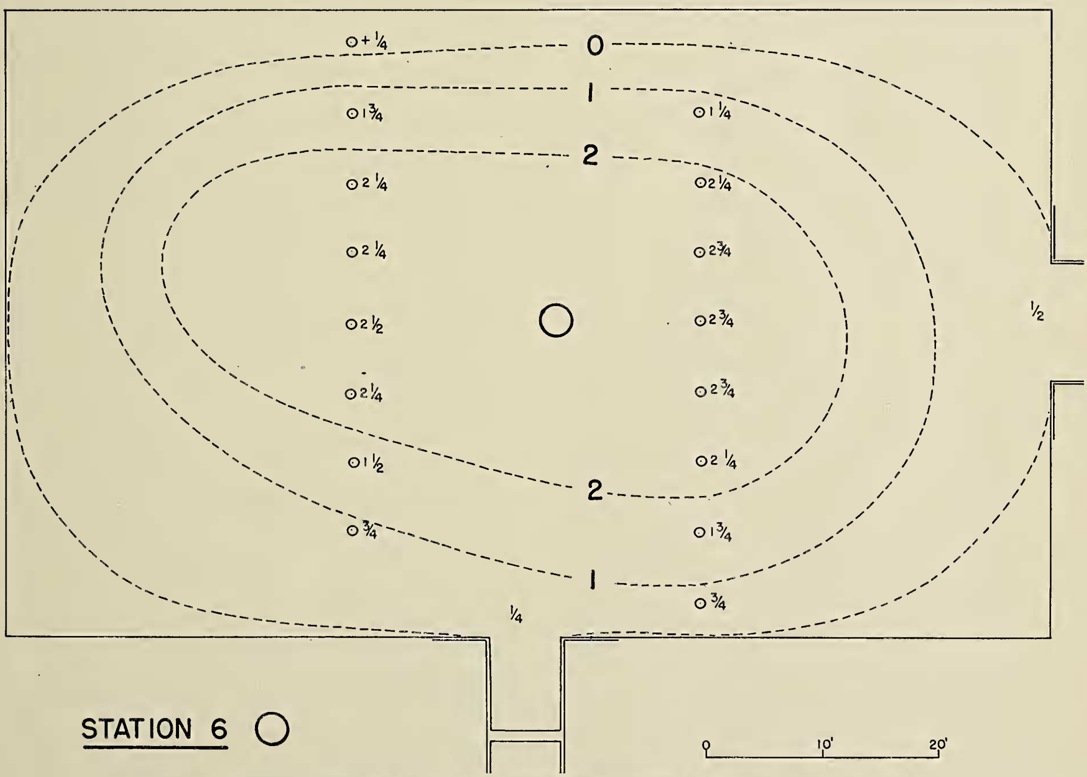

FIG. 6. Contour map of pond 3 showing depth in feet and location of station 6.

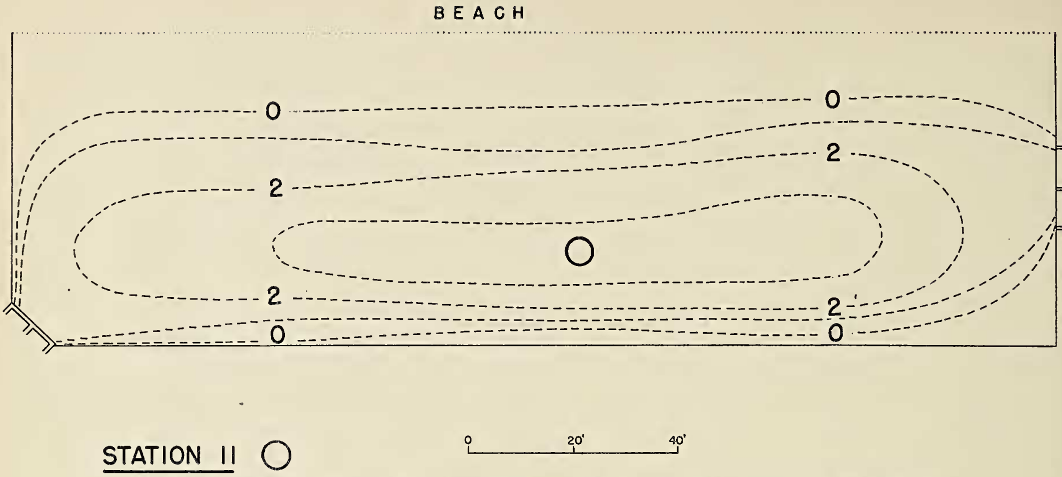

FIG. 7. Contour map of pond 6 showing depth in feet and location of station 11.

it longer than it can on an open ocean coast.

Because of the small amplitude of the lunar tide in Hawaii and because of the great influence of winds upon the tide in Kaneohe Bay, it is doubtful if the present data will permit the accurate establishment of either the zero tide line or the time differential with Honolulu tides.

However, for purposes of comparison an average zero tide line and a time differential were determined. Readings in the diurnal series of observations were taken every 15 minutes at the expected times of high and low water. The average zero tide reading was subtracted from these, and the corrected readings were then used in plotting and drawing the diurnal tidal curves for Kaneohe Bay (Fig. 9). In the first three sets of curves, interest was directed mainly to comparing the curves—tidal amplitudes as well as the correspondence of high and low waters. Hence, the initial high or low water of Kaneohe Bay and Honolulu were made to correspond with regard to time. The Kaneohe Bay tidal curve for the December series fitted the Honolulu curve poorly, especially with regard to correspondence of high and low waters. This was probably the result of stormy weather with variable winds during the period studied. The April and August series compared a little more favorably. The last set of curves was drawn mainly to compare the time differential between Kaneohe Bay and Honolulu. The April tidal curves were chosen for this comparison because they displayed the best fit of the three observations. The average time differential in this series was 1 hour 24 minutes, whereas the average time differential as determined in the study was 1 hour 50 minutes, and the time differential between the theoretical Honolulu tide and that of Waikane, Kaneohe Bay, the closest reference station, is 1 hour 35 minutes.

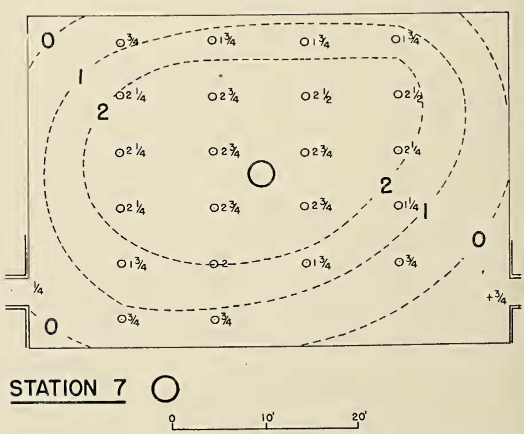

FIG. 8. Contour map of pond 4 showing depth in feet and location of station 7.

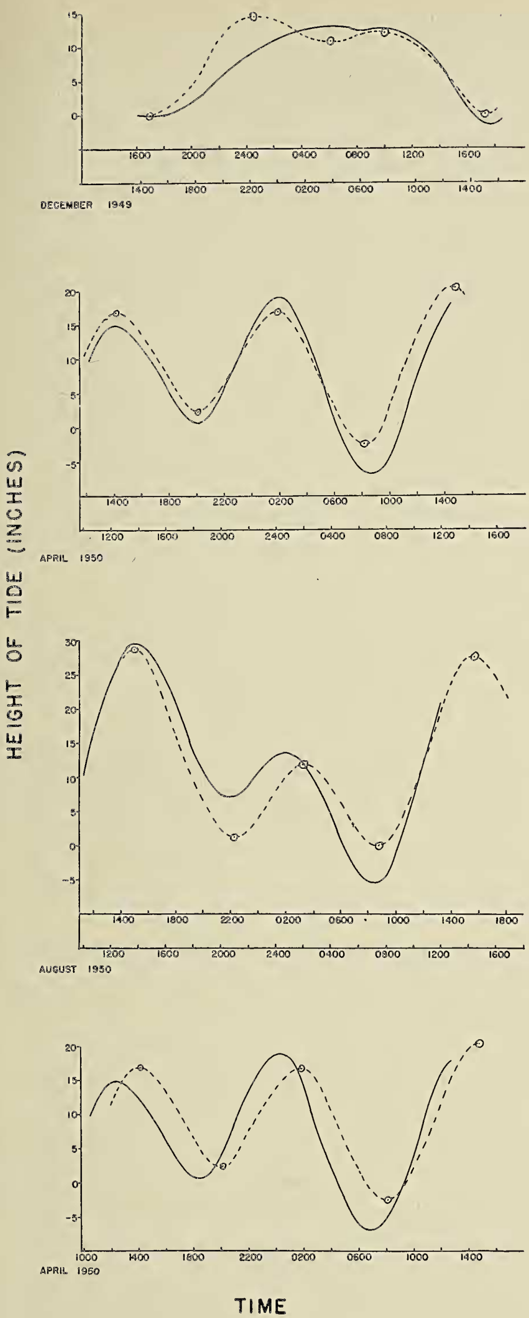

FIG. 9. Comparison of observed Kaneohe and theoretical Honolulu tidal curves. The upper three graphs compare the heights of the tides with the time adjusted so that the first tide of the cycle coincides. The bottom graph shows the actual difference in the time of the tide. The solid lines represent the Kaneohe data, the broken lines represent the Honolulu data.

METEOROLOGICAL CONDITIONS

Rainfall was measured by means of a standard rain gauge installed on Coconut Island in April, 1949 (Fig. 1, C). Measurements were read at weekly intervals, and the results were graphed (Fig. 10) to show seasonal variations. Values on the graph topped by a heavy horizontal line indicate that the rainfall during the week was greater than 2.10 inches, the upper limit of the rain gauge. Rainfall ranged from 0.00 inches to more than 2.10 inches, with the heaviest rainfall in both years occurring during the winter months.

Air temperatures were recorded by means of a continuous temperature recorder installed on April 3, 1949, in the net house (Fig. 1, B). Daily minimum and maximum temperatures were recorded and averaged to obtain weekly minimum and maximum temperatures, which were graphed to show seasonal variations. During the period studied, minimum air temperatures ranged from 19.3 to 24.3°C, and maximum air temperatures from 23.9 to 30.7°C. Both of the years studied exhibited a rapid drop of temperature from the highest in September and October to the lowest in November and December.

WATER TEMPERATURES

Water temperatures were obtained by means of a continuous temperature recorder and by sampling at intervals.

The water temperature recorder was installed on April 3, 1949, in the net house near station 2 (Fig. 1, B). Both surface and bottom water temperatures were taken. Top and bottom values for each day varied very little, therefore they were averaged, and the results were averaged again to obtain a weekly minimum and maximum. These weekly temperatures were then graphed to show seasonal variations. Minimum water temperatures as recorded on the continuous temperature recorder ranged from 21.5 to 27.0°C and maximum water temperatures from 21.8 to 27.2°C.

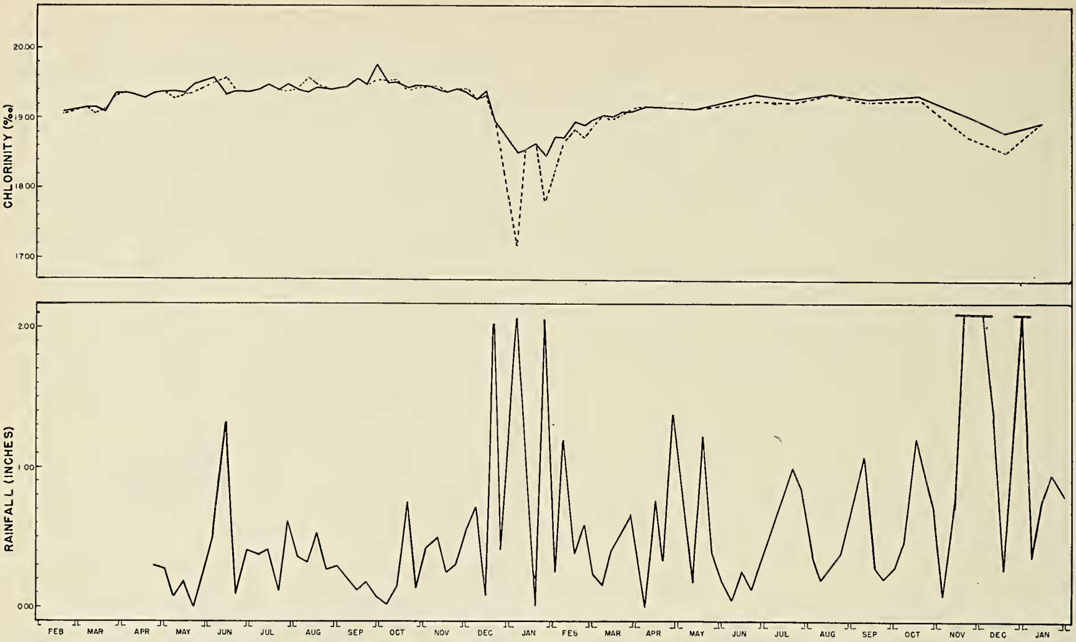

FIG. 10. Comparison of rainfall and chlorinity curves for a 2-year period from February, 1949, to February, 1951. Chlorinity of surface waters is indicated by broken lines, of bottom waters by solid lines.

In the sampling at intervals, at first both surface and bottom temperatures were taken weekly at all the stations where the depth of the water permitted, and bottom temperatures were taken at those stations where the water was too shallow to obtain differential samples with the modified oxygen sampler. As it was soon found that there was no great temperature differential between top and bottom at the shallow stations, 5, 6, 7, and 11, only one temperature was later taken at these stations, and as stations 4 and 6 were like stations 3 and 5, respectively, temperatures were taken monthly at stations 4 and 6. After March, 1950, temperatures were taken monthly at all stations.

Water temperatures were taken by means of a thermometer graduated in 1°C divisions and attached to the modified oxygen sampler. Temperatures were estimated to the closest 0.1°C and were graphed to show seasonal variations (Fig. 11), averages being used when the differential between top and bottom was less than 0.5°C. As expected, there was a close agreement of changes from station to station, and all stations showed a definite seasonal change. Deeper stations 1 and 2 showed the most gradual seasonal changes, and station 10, the very shallow station on the flats, showed the greatest extremes of temperature with a range from 20.5 to 33.3°C.

The extreme alternation between high and low temperatures on successive weeks, most noticeable in March and April, 1949, at station 10, was characteristic of the shallower stations and was the result of tidal differences. One week, at the time of sampling, the tide would be very low, while on the following week at the same hour it would be high. In weeks when the tide was low, the shallow waters were warmed and were not mixed with the cooler deep waters until the next flooding tide. In the following week when the tide was high at the same hour, the warmed waters were mixed with the cooler water brought in from the deeper channels.

Under normal conditions the surface waters tended to be warmer than bottom waters because of the warming effects of the sun and the decreased density of warmer water. However, during the winter months from December, 1949, to January, 1950, and from December, 1950, to January, 1951, the periods of "kona" weather and heavy rainfall (Fig. 10), a reverse situation was noted, and surface waters of lower temperatures were observed (Fig. 11). This was caused by the colder rain water floating on top of the warmer, more saline, and therefore more dense, bay water.

In the three 24-hour periods of observation, a definite diurnal change in temperature was found with a minimum temperature in the morning hours from 0500 to 0800 and a maximum temperature in the afternoon hours from 1200 to 1400 (Fig. 12). An increase of temperature range was noted from the December to the August series.

CHEMICAL CONDITIONS

Water samples for determining temperature, chlorinity, and oxygen content were collected simultaneously by means of the modified oxygen sampler. Water temperatures were recorded immediately, chlorinity samples were transferred from the reservoir bottle into citrate of magnesia bottles for storage, and oxygen samples were preserved immediately in the BOD bottles in which they were collected.

Chlorinity samples were analyzed by the Mohr technique (Thompson *et al.*, 1950: see section, "The Determination of the Chlorinity of Sea Water"; Kolthoff and Sandell, 1943: 568–570).

All chlorinity values were graphed to show seasonal variations and to compare some of the stations (Fig. 13). Averages were used when the differential between top and bottom was less than 0.25 parts per thousand. Chlorinities ranged from 14.94 parts per thousand to 19.88 parts per thousand. Throughout a greater part of the year, chlorinities did not show much variation until the great drop in chlorinity found in the winter months of January, 1950, and December, 1950, and associated with the onset of heavy rainstorms (Fig. 10). To show the influence of rainfall on salinity, data were gathered routinely and compared with the chlorinity values of representative station 2 (Fig. 10).

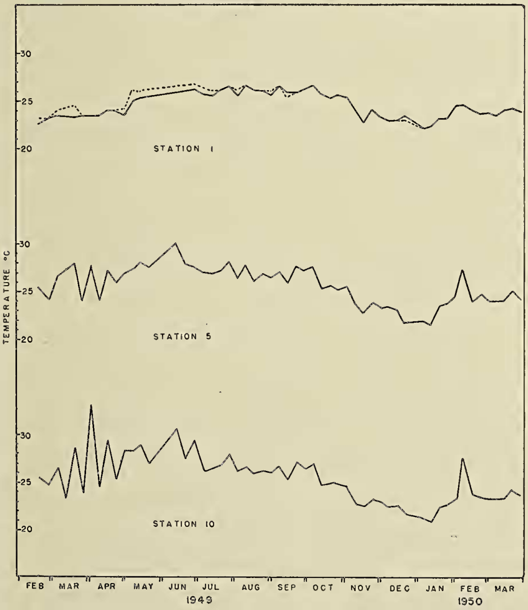

FIG. 11. Comparison of water temperatures for a year at stations 1, 5, and 10. Temperature of surface waters shown by broken line, of bottom waters by solid line.

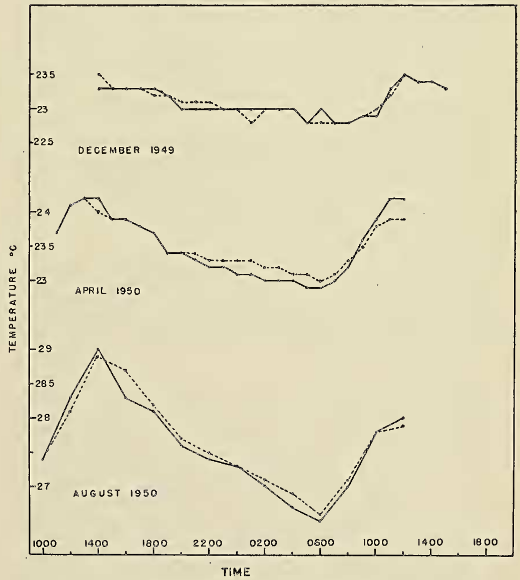

FIG. 12. Comparison of water temperatures for three diurnal observations. Temperature of surface waters shown by broken line, of bottom waters by solid line.

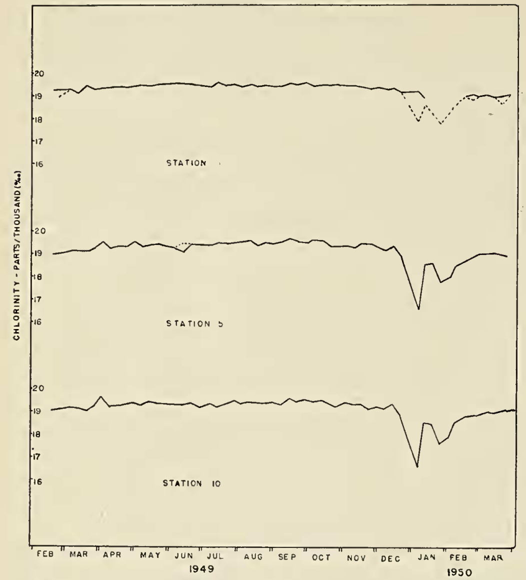

FIG. 13. Comparison of chlorinity for a year at stations 1, 5, and 10. Chlorinity of surface waters shown by broken line, of bottom waters by solid line.

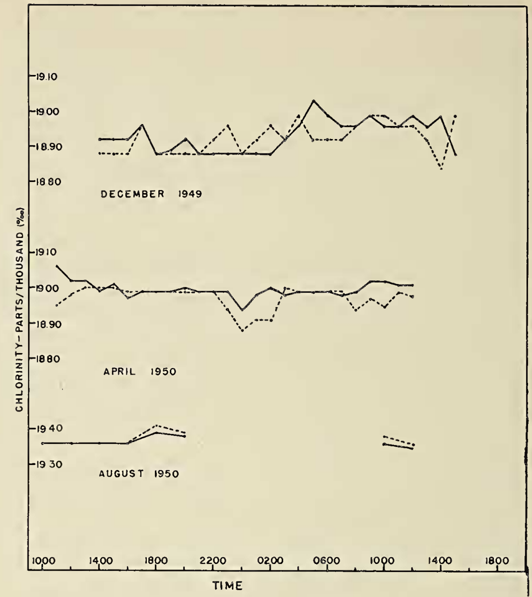

FIG. 14. Comparison of chlorinity for three diurnal observations. Chlorinity of surface waters shown by broken line, of bottom waters by solid line. Part of August samples were lost, hence break in graph.

The surface layers were especially affected by these rainstorms. In the shallow stations, 5, 6, 7, 10, and 11, where only one sample was taken, chlorinities dropped to about the same degree as the surface waters of the deeper stations such as 1 and 2. The surface layer of brackish water lost its separate identity after about a month, and deep and shallow water became almost homogeneous but of a lowered chlorinity. In the winter season of 1949–50, about 2 months were required for the chlorinity values to resume a normal level after the heavy rains.

In the 24-hour cycles, no diurnal changes in chlorinity were observed which could be correlated with either day and night or with tides (Fig. 14).

Oxygen samples were determined by the Winkler method for dissolved oxygen (Hollister, 1950: see section, "Determination of Dissolved Oxygen in Fresh and Sea Water"; Kolthoff and Sandell, *op. cit.*, pp. 614–619). All oxygen values were graphed to show seasonal variations and to compare some of the stations (Fig. 15). Averages were used when the differential between top and bottom was less than 0.25 milliliters of oxygen at normal temperature and pressure per liter of sea water at 20°C. From the beginning of sampling to mid-July, 1949, sampling was done in the early afternoon with the few exceptions noted. These afternoon values were, on the whole, higher than the morning values. Values ranged from 1.10 milliliters per liter to 7.27 milliliters per liter, these extreme values being the exception rather than the rule. On the whole, no marked seasonal pattern was detected, and diurnal changes were more noticeable.

Oxygen concentration displayed a definite diurnal change (Fig. 16) in all three 24-hour cycles, reaching a minimum in the morning between 0500 and 0700 and a maximum in the afternoon between 1400 and 1800. This diurnal change is presumably related to the biochemical activity of plants producing an excess of oxygen in hours of daylight and the consumption of oxygen by both plants and animals in the hours of darkness.

Saturation values were determined (computations based on Table 24, Harvey, 1928:

TABLE 2
Diurnal Changes in Oxygen Content

DATE	TIME	OBSERVED VALUE	COMPUTED SATURATION VALUE	PERCENTAGE SATURATION
		ml./L.	*ml./L.*	
December 27–28, 1949..........	1400 maximum	5.29	5.08	104
	1800 median	4.70	5.10	92
	0500 minimum	4.10	5.14	80
April 28–29, 1950..............	1600 maximum	5.41	5.04	107
	0200 median	4.82	5.11	94
	0700 minimum	4.23	5.10	83
August 25–26, 1950............	1800 maximum	4.82	4.65	104
	2200 median	4.43	4.71	94
	0600 minimum	4.02	4.79	84

60) for the minimum, median, and maximum oxygen content values in each of the 24-hour cycles. Results tabulated in Table 2 show that the minimum morning values represent undersaturated waters and the maximum afternoon values represent supersaturated water. All three observations show a similar cycle with regard to the amount of oxygen dissolved in the water.

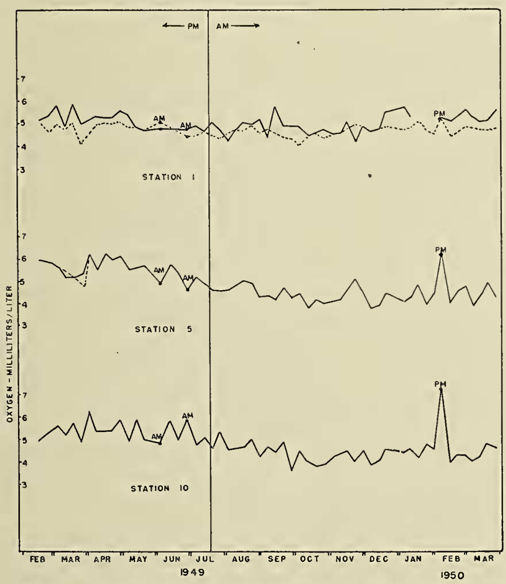

Fig. 15. Comparison of oxygen content for a year at stations 1, 5, and 10. Oxygen content of surface waters shown by broken line, of bottom waters by solid line. Unless otherwise indicated, samples for the first 5½ months were collected in the afternoon, thereafter in the mornings.

At monthly intervals for over a year analyses were attempted for the nutrient salts, phosphates, nitrites, and silicates. As the analytical methods were colorimetric, attempts were first made to measure the color intensities with a Klett-Sommerson photoelectric colorimeter, test tube model. Because of the

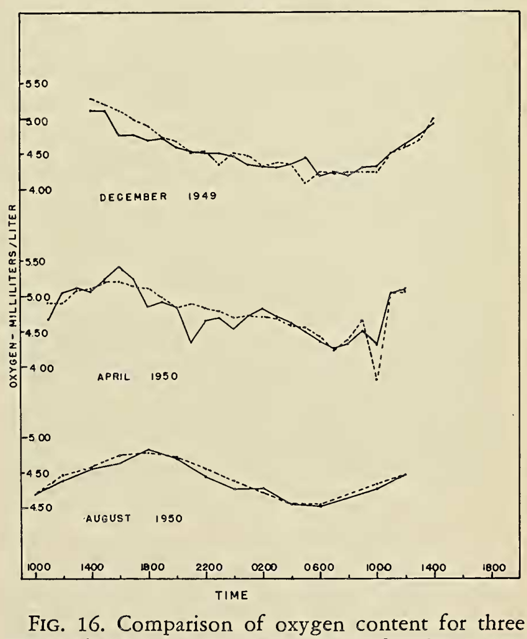

Fig. 16. Comparison of oxygen content for three diurnal observations. Oxygen content of surface waters shown by broken line, of bottom waters by solid line.

limitations of the instrument, attempts were then made to measure the color intensities with a Beckman spectrophotometer, model B. With neither instrument were the tests or the measuring apparatus sufficiently accurate to give reliable results with the low concentrations of these salts present.

Inorganic phosphates were analyzed by a modification of the method of Deniges (as reported by Robinson and Thompson, 1948*a*: 33–41). From the attempted analyses it can be concluded that no samples taken during the year greatly exceeded the value of 0.50 mygram atoms per liter and that it is likely that most values were lower.

Nitrites were analyzed by a method originally developed by Peter Griess and later modified by Ilosvay (as reported by Robinson and Thompson, 1948*b:* 42–48). None of the samples taken throughout the year gave measurable amounts of nitrite; therefore, the nitrite was either almost entirely absent from the waters or at least fell consistently below 0.10 mygram atoms per liter.

Silicates were analyzed by a modification of a method made practical by Dienert and Wandenbulcke and first applied to oceanographic investigations by Atkins (as reported by Robinson and Thompson, 1948*c:* 49–55). With regard to the silicates it can be stated that no samples taken during the year greatly exceeded the value of 10 mygram atoms per liter and that it is likely that most values were lower.

REFERENCES

HARVEY, H. W. 1928. *Biological chemistry and physics of sea water.* x + 194 pp. The Macmillan Company, New York.

HOLLISTER, H. J. 1950. Determination of dissolved oxygen in fresh and sea water. [Separate pagination.] *Manual of oceanographic methods.* Canadian Joint Committee on Oceanography, Pacific Oceanographic Group, Nanaimo, B. C., Canada. [Mimeographed.]

KOLTHOFF, I. M., and E. B. SANDELL. 1943. *Textbook of quantitative inorganic analysis.* xvii + 794 pp. The Macmillan Company, New York.

MARMER, H. A. 1926. *The tide.* xi + 282 pp. D. Appleton and Co., New York.

ROBINSON, REX J., and THOMAS G. THOMPSON. 1948*a*. The determination of phosphate in sea water. *Jour. Marine Res.* 7(1): 33–41.

——— and ——— 1948*b*. The determination of nitrites in sea water. *Jour. Marine Res.* 7(1): 42–48.

——— and ——— 1948*c*. The determination of silicates in sea water. *Jour. Marine Res.* 7(1): 49–55.

SVERDRUP, H. U., MARTIN W. JOHNSON, and RICHARD W. FLEMING. 1946. *The oceans, their physics, chemistry, and general biology.* x + 1087 pp. Prentice-Hall, Inc., New York.

THOMPSON, T. G., *et al.* 1950. The determination of the chlorinity of sea water. [Separate pagination.] *Manual of oceanographic methods.* Canadian Joint Committee on Oceanography, Pacific Oceanographic Group, Nanaimo, B. C., Canada. [Mimeographed.]

UNITED STATES COAST AND GEODETIC SURVEY. 1949 (also 1950 and 1951). *Tide tables, West Coast, North and South America (including the Hawaiian Islands).* 206 pp. U. S. Department of Commerce, Washington.

WELCH, PAUL S. 1948. *Limnological methods.* xviii + 381 pp. The Blakiston Co., Philadelphia and Toronto.